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(54) Method for winding the coils for an air gap motor.

(57) There is described a method for making the winding of the stator coils of an electric motor, said method comprising the steps of winding the coils in a predetermined cavity; bonding the individual coils together while in the cavity using bondable magnet wire; and nesting individual coils together to form a multi-phase stator winding while in the cavity.

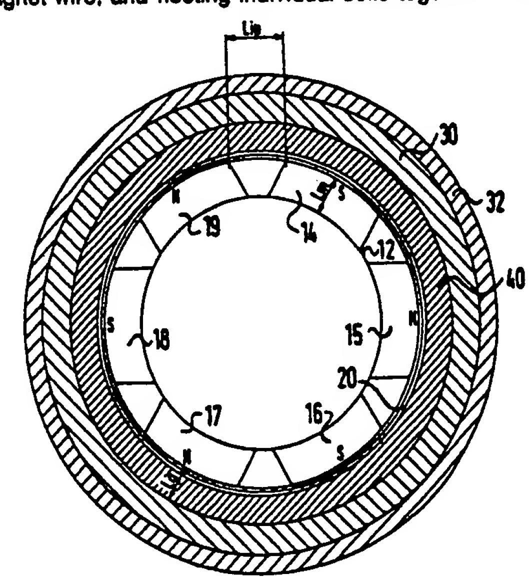

FIG. 1

The invention relates to a method for winding the coils for a high performance servo motor which makes effective use of high energy product permanent magnets. Recently, new typ s of permanent magnets have become available with significantly increased energy products. These new magnets comprise alloys of a rare earth, usually neodymium or praseodymium, iron, and a promoter of metastable phases such as boron or gallium, as disclosed in US-Serial No. 470,968 filed March 1, 1983. Prior alnico (aluminum-nickel-cobalt) magnets usually have an energy product in the range of 5 to 7 MGOe (Mega-Gauss Oersteds), samarium-cobalt $SmCo_5$ magnets have an energy product of about 17 MGOe, and more expensive samarium-cobalt Sm_2Co_{17} magnets have an energy product of about 27 MGOe.

Neodymium-iron-boron magnets are now available having energy products in excess of 35 MGOe.

The object of this invention is to provide a method for the efficient winding of coils for motor designs which can make effective use of high energy product permanent magnet materials having an energy product of above 26 MGOe and preferably above 30 MGOe.

It is also an object of this invention to provide a method of making high performance motors with windings located in the motor air gap.

There is disclosed herein a method of making an electric motor with the stator winding inside a slotless cylindrical stator shell of magnetic material comprising the steps of forming a slotless cylindrical stator shell of magnetic material, creating a generally cylindrical support with a reduced diameter portion at one end, forming the winding around said support from preformed coils such that the coil end turns at the reduced diameter portion of said support flare inwardly, and the coil end turns at the other end of said support flare outwardly, inserting said winding into said cylindrical stator shell starting with the inwardly flared end coils, removing said support from said end of said outwardly flared end coils, and impregnating said winding with a resin to secure said winding inside the stator shell, characterized in that the winding of the stator coils is produced by a method comprising the steps of winding the motor phase coils into a predetermined cavity; bonding the individual coils together while in the cavity using bondable magnet wire; and nesting individual coils together to form a multi-phase stator winding.

At room temperature, NdFeB magnets, like samarium-cobalt magnets, do not show any significant demagnetization characteristics. At elevated temperatures above 100°C, and particularly above 140°C, however, the coercivity of the NdFeB magnet falls off rapidly beyond a "knee" and, hence, demagnetization can occur. Since the demagnetization force applied to the magnet is proportional to armature current, a conventional design using NdFeB magnets will have limited peak current and, therefore, low peak torque despite higher energy product magnets. As described in co-pending patent application 86102832.2 it has been found that the benefits of the new high energy product magnets (above 26 MGOe and preferably above 30 MGOe) can be realized by using a slotless design provided certain design parameters ar observed. The stator winding is a multi-phase winding contained wholly within the magnetic air gap so that there are no saturation constraints in the magnetic circuit and flux densities above 7 kilogauss in the air gap can be used. The ratio of the magnet length to the air gap length is in the range of 0.5 to 2.0. The ratio of the interpolar distance to the radial gap length is greater than 1.3. By staying within these design parameters motors can be constructed using the high energy product magnets without danger of demagnetization and with significantly increased horsepower and continuous torque for a given size and weight.

Furthermore, the motor according to co-pending patent application 86.102832.2 has a reduced inductance which provides more power at high speeds and a lack of reluctance torque and cogging.

A comparison of prior samarium-cobalt (Sm_2Co_{17}) magnet servo motors with motors of comparable size and weight made according to this invention indicates about a 70% increase in the dynamic continuous torque speed output performance and about an 80% increase in the intermittent performance.

The winding must be properly secured within the surrounding back iron cylindrical shell which provides the flux return path with sufficient adhesion to withstand the maximum motor torque force throughout a range of operating temperatures. It must be rigid since movement of the conductors adversely affects the ability to generate torque. Also, heat must be dissipated from the windings. To achieve these objects, the winding is encapsulated and bonded to the cylindrical stator shell by a ceramic filled epoxy selected to provide (1) a good mechanical strength (i.e., compressive strength, tensile strength, tensile shear), (2) good thermal conductivity, and (3) a coefficient of thermal expansion equal to or greater than that of other materials in the stator structure. One suitable material is Nordbak 7451-0148/7540-0027 epoxy, another is Stycast 2762 .

The winding is formed using a cylindrical support with a reduced diameter section at one end. In one embodiment of this invention, a fiberglass sleeve is placed around the cylindrical support in the uniform diameter portion and thereafter preformed coils are placed in position. It is understood that the fiberglass sleeve is not necessary to support the coils.

The invention additionally describes a method for winding the coils of the air gap motor to achieve a

winding having a set of end turns at one end that flare inwardly toward the rotor, and another s t at the other end that flare outwardly away from the rotor. To achieve the winding, each coil is wound in a defined coil form and then held in that shape by means of a cement coating on the wire (bondable wire). The coils are then nested together on the cylindrical support to define the desired shape of the winding. Through this method the windings may be made automatically by machine.

The winding can then be inserted into the cylindrical back iron shell starting with the inwardly flared end of the winding. The support can thereafter be withdrawn from the outwardly flared end of the winding leaving the fiberglass sleeve in as part of the stator structure. The winding is preferably encapsulated using a suitable resin after the winding is inserted into the stator shell. Notched laminations can be used in the stator shell to improve the shear strength of the bond between the winding and the stator shell. The notches are randomly distributed along the axial length of the machine to aliminate any appearance of a reluctance effect.

Fig. 1 is a cross-sectional end view of the motor of copending patent application No. 86.102832.2.

Fig. 2A and Fig. 2B are a side view and end view, respectively, of the rotor portion of the motor of Fig. 1.

Fig. 3 is a cross-sectional view of the stator of the motor of Fig. 1.

Fig. 4 shows the lapped winding structure in the motor of Fig. 1.

Fig. 5 is a diagram showing the demagnetization curves of a high energy product permanent magnet of the type used in the motor of Fig. 1.

Fig. 6 shows the improved operating performance of the motor of Fig. 1 as compared to a prior motor with samarium-cobalt magnets having comparable size.

Fig. 7 is an axial view of a portion of the winding showing outwardly flared end turns.

Fig. 8 is an axial view of a portion of the winding showing inwardly flared end turns.

Fig. 9 is a top view of the coil form showing sectional lines.

Fig. 10 is a plan view of a portion of the coil form.

Fig. 11 is a plan view of the downward bottom form portion of the coil form.

Figures 1 to 3 show the general structure of the motor according to co-pending patent application No. 86102832.2 The motor includes a steel shaft 10 surrounded by a cylindrical iron sleeve 12 which provides the back iron for the rotor (Fig. 2A and 2B). Six permanent magnets 14-19 are mounted on sleeve 12 extending radially and are magnetized to provide alternating north and south poles as shown in Fig. 1. Th magnets are high energy product magnets with energy products in excess of 26 MGOe and preferably in excess of 30 MGOe. Suitable permanent magnets are those made from neodymium, iron and boron (NEOMAX-30H®). The magnets are pressed arcuate shaped magnets and are mounted on the back iron sleeve 12 surrounding shaft 10.

A banding 20 surrounds the rotor structure to hold the magnets in place under high speed centrifugal force conditions. Banding is accomplished using high strength Kevlar filaments which are dipped in epoxy and then wound around the rotor including one or more helical layers followed by several hoop layers.

The rotor can be constructed using six magnets each extending the full length of the rotor, or the magnets can be segmented as shown in Fig. 2A. An advantage to the segmented magnets is that a singl motor design can produce motors of different horsepower ratings by simply changing the motor length and the number of magnet segments.

The stator structure includes a cylindrical outer shell 30 of laminated silicon steel which provides th outer back iron for the motor. The laminates are assembled and then cast in an aluminum outer housing 32. The windings 40 are formed and then mounted inside the cylindrical back iron shell.

The motor in the illustrative embodiment is a six pole three phase winding and, therefore, includes eighteen (18) coils in the winding. The coils are preformed and then placed in a lapped configuration as shown in Fig. 4. A coil 41 of phase A is followed by a coil 42 of phase B which, in turn, is followed by a coil 43 of phase C, and then the sequence repeats. The longitudinal conductors 44 of one side of a coil are on the outside of the winding whereas the longitudinal conductors 45 of the other side of the same coil are on the inside of the winding beneath the conductors 46 of the next coil of the same phase.

According to this invention, the winding is formed by nesting phase coils. For the six pole three phase motor illustrated in Fig. 1-3 eighteen phase coils are nested to form the winding (s. Fig. 4).

Fig. 7 illustrates th nesting of coils from an axial view at the end having outwardly flared end turns. Similarly, Fig. 8 illustrates the nesting of coils from an axial view at the end having inwardly flared end turns. The coils in the end turn regions both turn and raise continuously to achieve the three phase winding. Each coil has the same coil shape and n sts on each of the other coils. Coils 70 and 76 (Figs. 7 and 8) are at a phase A, while coil 72 is at a phase B, and coil 74 is at a phase C. The arc distances over which a coil is the outer coil of the winding are defined by a coil form which is used to form each coil. The arc distance

is related to the arc distance that the poles occupy within the motor.

Referring to Figures 9-11, a preferred embodiment of the coil form 80 is illustrated. Fig. 9 shows a top view of the coil form with the sectional lines showing. A winding is formed by feeding wir into the coil form 80 (Figs. 10 and 11) which has a predetermined coil cavity to give the coil the desired shape. The wire is shaped against the coil form with the sectional lines being the points where the transitions in the coil are formed. The coil transitions can be seen in Figures 7 and 8. Each coil is made up of a lower coil side and an upper coil side. The coil is bonded together while in the cavity using bondable magnet wire to form the coil.

By forming the coils in this manner, the process may be highly automated. For example, a machine can wind the coils into the coil form 80. In addition, insertion of the coils into the shell 30 does not require any additional shaping or forming of the coils. Because the windings do not need to be molded in place and the coils are nested into their true positions, the generated back EMF is consistent between phases, resulting in smoother performance of the motor. The coil form includes a downward bottom form 100, an upward bottom form 102, an upward top form 104, a downward top form 106, a top plate 108 and a bottom plate 110.

The resin material must be carefully selected for the motor according to the invention. The resin should have a good mechanical strength (i.e., compressive strength, tensile strength, tensile shear, etc.) in order to rigidify the winding since any freedom of movement adversely affects the ability of the winding to produce torque. The motor is designed for continuous operation at 150°C and must be capable of withstanding peak temperatures of over 200°C. The thermal expansion of the resin must, therefore, be equal to or greater than that of the surrounding materials.

The rating of the motor depends largely on the ability to dissipate heat from the windings and, therefore, the resin must also provide good thermal conductivity, preferably in the range above 0.0026 (cal)-(cm)/(sec)(cm^2)(°C). This is particularly true with the compact motor design resulting from the invention. Ceramic fillers are preferably incorporated in the resin to improve thermal conductivity. However, the ceramic fillers must be non-conductive and non-magnetic in order to avoid eddy current and iron losses. Furthermore, the resin must have a low viscosity below 50 000 cps in the uncured state in order to properly impregnate the winding.

A suitable thermally conductive resin is Nordbak 7451-0148/7450-0027® epoxy. The typical properties for this epoxy are as follows:

Application Characteristics

Viscosity (cps) (ASTM D-2393)			
Resin	25°C	250 000 - 300 000
Hardener	25°C	500 - 1 000
Mixed	25°C	6 000 - 8 000
	85°C	500 - 600

Gel Time, 50 g mass
(ASTM D-2472)
121°C 30 - 40 min.

Cure Cycle
Cure at 82°C for 4-6 hours followed by a post cure at a min. of 121°C for 3-4 hours.
Post cure at operating temperature is recommended.

Mixing Ratio
By weight 5.0 parts resin to 1.0 part hardener
By volume 3.0 parts resin to 1.0 part hardener

Color
Resin Black

Hardener Brown
Mixed Black

Density (kg/l)
Resin 1.89
Hardener 1.19
Mixed 1.73

Typical Cured Properties Compressive Strength (kg/cm^2)
(ASTM D-695)
52 900

Tensile Strength (kg/cm^2)
(ASTM D-638)
20 000

Elongation (%)
(ASTM D-638)
6.3

Linear Shrinkage (cm/cm)
(ASTM D-2566)
0.007

Hardness (Shore D)
(ASTM D-2240)
25°C 90
180°C 67

Tensile Shear (kg/cm^2)
(ASTM D-1002)
7 700

Water Absorption (%)
(MIL-STD 406, Method 7031)
0.20

Outgassing (%)
(NASA Spec.ST-R-0022)
CVCM 0.06

Coefficient of Thermal Expansion
10^{-5} cm/cm °C
below 50°C 4.36
59 - 104°C 7.20
above 104°C 12.20

Thermal Conductivity at 70°C
(cal)(cm)/(sec)(cm^2)(°C)
0.0026

Typical Electrical Properties Dielectric Constant (ASTM D-150)
100 Hz 4.1
1 KHz 4.1
10 KHz 4.0
100 KHz 4.0

Dissipation Factor (ASTM D-150)
100 Hz 0.003
1 KHz 0.004
10 KHz 0.004
100 KHz 0.008

Volume Resistivity (ohm-cm)
(ASTM D-257)
1.6×10^{15}

Dielectric Strength (V/ml)
(ASTM D-149)
450

Variations7451-0012/7450-0027®
Unfilled, high elongation
7451-0148/7450-0022®
More flexible 70 Shore D

Another suitable thermally conductive resin is Stycast 2762® epoxy resin. The typical properties for this resin are as follows:

PhysicalSpecific gravity 2.2
Flexural strength (kg/cm²)
at 21°C 759
at 149°C 539
at 250°C 315
Flexural modulus (kg/cm²)
at 21°C 84 000
at 149°C 70 000
Water absorption (5 gain at 25°C - 24 hours) 0.02
Thermal conductivity
(cal)(cm)/(sec)(cm²)(°C) 0.0033
Hardness (Shore D) 96
Compressive strength (kg/cm²) 1 260
Elastic modulus (kg/cm²) 84 000
Thermal expansion (/°C) 27×10^{6}

Electrical

	Temp. (°C)	Dielectric Constant	Dissipation Factor
at 60 Hz	21	4.3	0.007
	149	4.4	0.008
Dielectric strength (kV/mm)	21	16.0	
	149	14.8	
Volume resistivity (ohm-cm)	21	10^{16}	
	149	10^{11}	

When the winding is in place in the cylindrical outer shell of the stator, the epoxy is forced into the winding cavity at one end under pressure and is drawn through the winding by means of a vacuum applied at the other end. When the epoxy cures the winding becomes rigid and is securely bonded to the stator laminations. The ends of the winding cavity preferably flare out at both ends in the region of the end turns to increase the surface area. The end surfaces can be machined to provide a flat surface for good thermal contact with the end bells of the motor (not shown). In most cases, however, good thermal contact between the resin and the aluminum housing 32 will provide adequate heat dissipation.

The demagnetization curves of a suitable magnet material, for example NEOMAX-30H®, are shown in Fig. 5. For temperatures below 100°C the properties are substantially linear and, hence, no demagnetization is likely to occur when operating in this temperature range. At elevated temperatures above 100°C, however, there is a "knee" in the curve which, at 140°C, occurs at Bd = 3 500 Gauss and Hd = 6 000 Oersteds. The rapid falloff of the coercivity at field strengths higher than 6 000 Oersteds can cause significant demagnetization of the magnets. The permeance P is the operating slope of the magnet in a given circuit. The slope is given by $P = \frac{Lm}{Lg}\,\frac{Ag}{Am}$ where

Lm = magnet length and orientation
Lg = length of the magnetic gap
Am = area of magnet and
Ag = area of gap.

The allowable demagnetization field Ha is given by a line having slope P + 1 and passing through (Hd, Bd) at the knee in the curve. This can be written as

$$Ha = Hd - \frac{Bd}{(P+1)}$$

Substituting for P and simplifying the equation becomes

$$Ha = Hd - \frac{Bd\ Lg\ Am}{Lm\ Ag + Lg\ Am} \quad \text{in Oersteds} \qquad (1)$$

Thus, the maximum allowable demagnetization field Ha can be calculated for a given demagnetization characteristic and operating permeance P.

For design comparison purposes, the worst case demagnetization field is when the stator currents are arranged such that the stator MMF directly opposes the magnet MMF. This is a realistic case since many servos are braked by shorting phase leads together, thus giving such a field alignment. Current in phase A is peak and current in phases B and C is 1/2 the peak current value. By symmetry, the armature H field is

radial at the centerline of the magnet. Taking this path, the enclosed ampere turns per pole is

$$NI = \frac{C}{2\ \text{poles}} \qquad 2\ (\text{Ipeak})$$

where C is series conductors per phase.From Ampere's Law

$$H = \frac{NI}{L} = \frac{C\ \text{Ipeak}}{\text{Poles}\ (Lg + Lm)\ 2.021}\ \text{in Oersteds} \quad (2)$$

Thus, for a given combination of poles, gap length, magnet length, conductors, and current, the applied demagnetization field H can be calculated.

Solving equation (2) for Ipeak and setting the allowable applied demagnetization field Ha equal to the applied field H, gives

$$Ip = \frac{H\ \text{Poles}\ (Lg + Lm)\ 2.021}{C}\ \text{in amperes}$$

Substituting equation (1) for H gives

$$Ip = \frac{\left[Hd\ (Lm\,Ag + Lg\,Am) - Bd\,Am\,Lg\right]\ P\,(Lg + Lm)\ 2.021}{(Lm\,Ag - Lg\,Am)\ C} \quad (3)$$

Therefore, the maximum allowable peak current before demagnetization is expressed as a function of magnet material (Bd, Hd) and magnetic circuit design (poles, Lm, Lg, Am, Ag, C).

The various parameters of equation (3) for the conventional slotted design and the air gap winding design of the invention, both using the NdFeB magnet material shown in Fig. 5 with (Hd, Bd) of (6 000, 3 500) are as follows:

TABLE 1.

	Units	Invention	Slotted Motor
Bd	Gauss	3 500	3 500
Hd	Oersteds	6 000	6 000
Lm	mm	9.6	3.18
Lg	mm	7.6	1.25
Am	mm^2	28.63	18.82
Ag	mm^2	32.36	18.82
Poles		6	6
C		168	198
Ipeak	Amperes	223.8	53.4
I_{RMS}	Amperes	158.2	37.8

As can be seen from Table 1, the air gap winding design allows more than four times the peak torque allowed by the conventional slotted design. With a maximum of 37.8 A RMS current before demagnetization, the conventional slotted design does not offer the needed peak torque for a high responsive servo

motor.

If the air gap is made relatively large, such as 8.5 mm in the illustrative embodiment of the invention, the reluctance of the magnetic path for flux generated in the stator is sufficiently high such that the flux, as seen by the magnets, remains below the level at which demagnetization is likely to occur. The ratio of the air gap length (Lg) to the magnet length (Lm), Fig. 1, must be in the range between 0.5 and 2.0. The use of permeances in the range of 4 to 6, common in slotted motor structures, is undesirable since it results in either an excessively large amount of expensive permanent magnet material or a small air gap inadequate to hold the desired number of windings required for a high performance motor.

The ratio of the interpolar distance (Lip) to the radial gap length (Lg), as seen in Fig. 1, should be greater than 1.3. With high energy product magnets this ratio becomes important since a lower ratio results in ineffective use of the expensive permanent magnet materials due to increasingly high leakage flux.

Fig. 6 is a diagram illustrating the dynamic comparison of two motors with approximately the same outside physical dimensions. Curves 60 and 61 are for a conventional slotted structure with samarium-cobalt (Sm_2Co_{17}) magnets having an energy product of about 27 MGOe, whereas curves 62 and 63 are for a motor according to the invention including permanent magnets, eg the NdFeB type with an energy product of about 35 MGOe. Area A represents an increase of about 70% additional continuous performance while area B shows about an 80& increase in the intermittent performance. These improvements in the operating characteristics are achieved with an increase of only about 30% in the energy product of the permanent magnets.

Claims

1. A method of making an electric motor with the stator winding inside a slotless cylindrical stator shell of magnetic material comprising the steps of forming a slotless cylindrical stator shell of magnetic material, creating a generally cylindrical support with a reduced diameter portion at one end, forming the winding around said support from preformed coils such that the coil end turns at the reduced diameter portion of said support flare inwardly, and the coil end turns at the other end of said support flare outwardly, inserting said winding into said cylindrical stator shell starting with the inwardly flared end coils, removing said support from said end of said outwardly flared end coils, and impregnating said winding with a resin to secure said winding inside the stator shell, **characterized** in that the winding of the stator coils is produced by a method comprising the steps of

-winding the motor phase coils into a predetermined cavity;

-bonding the individual coils together while in the cavity using bondable magnet wire; and

-nesting individual coils together to form a multi-phase stator winding.

2. The method of claim 1, characterized in that the motor phase coils are automatically wound into a predetermined cavity.

3. The method of claim 1, characterized in that the coils are automatically bound together while in the cavity.

4. The method of claim 1, characterized in that the coils are nested to form a three phase stator winding.

5. The method of claim 1, characterized in that said resin has a thermal conductivity in excess of 0.0026 (cal)(cm)/(sec)(cm^2)(°C)

6. The method of claim 1, characterized in that said resin has a coefficient of thermal expansion equal to or greater than that of the cylindrical stator shell.

7. The method of claim 1, characterized in that said resin is an epoxy filled with a non-conductive and non-magnetic ceramic.

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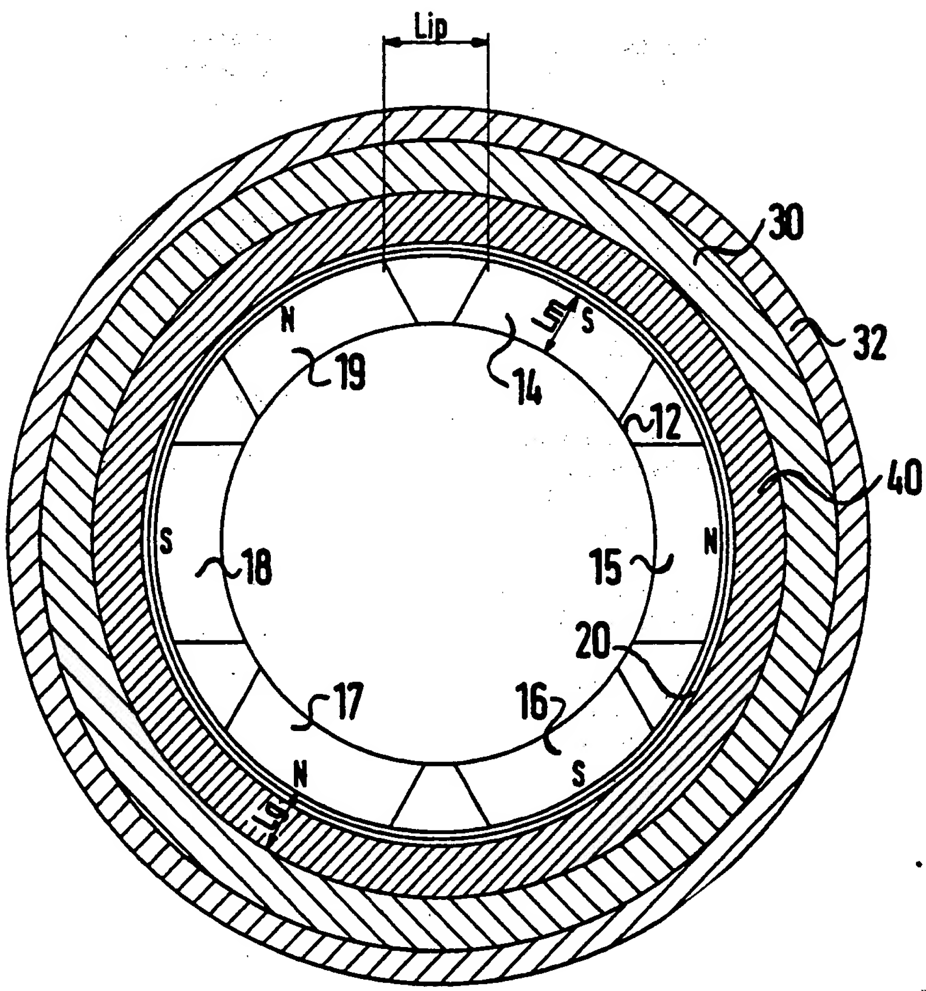


FIG. 1

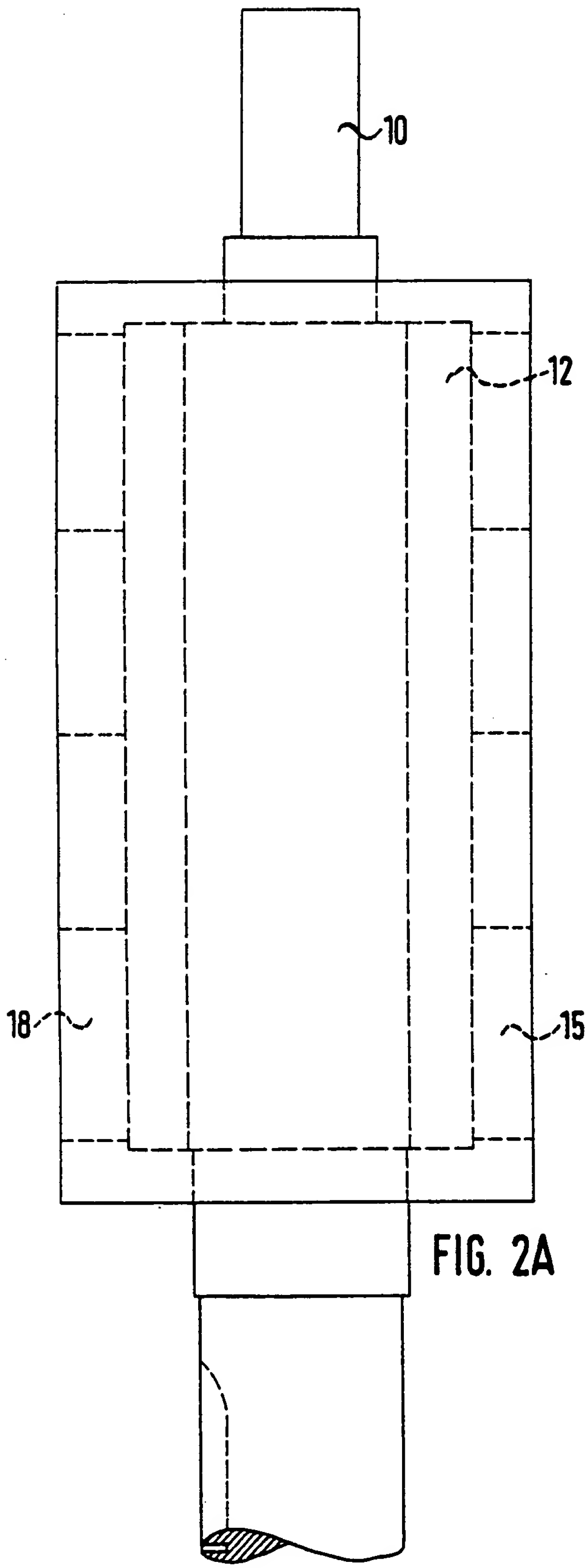


FIG. 2A

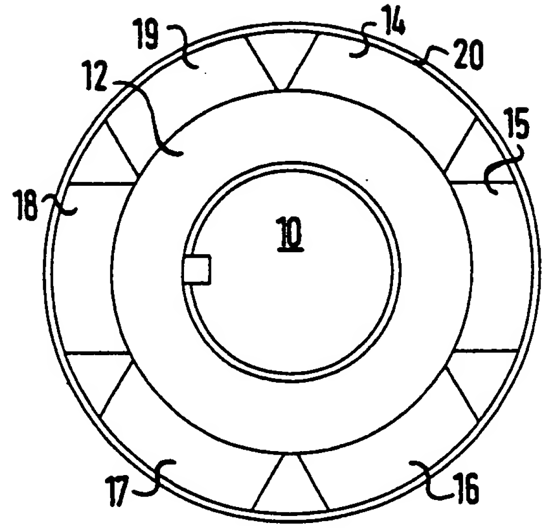


FIG. 2B

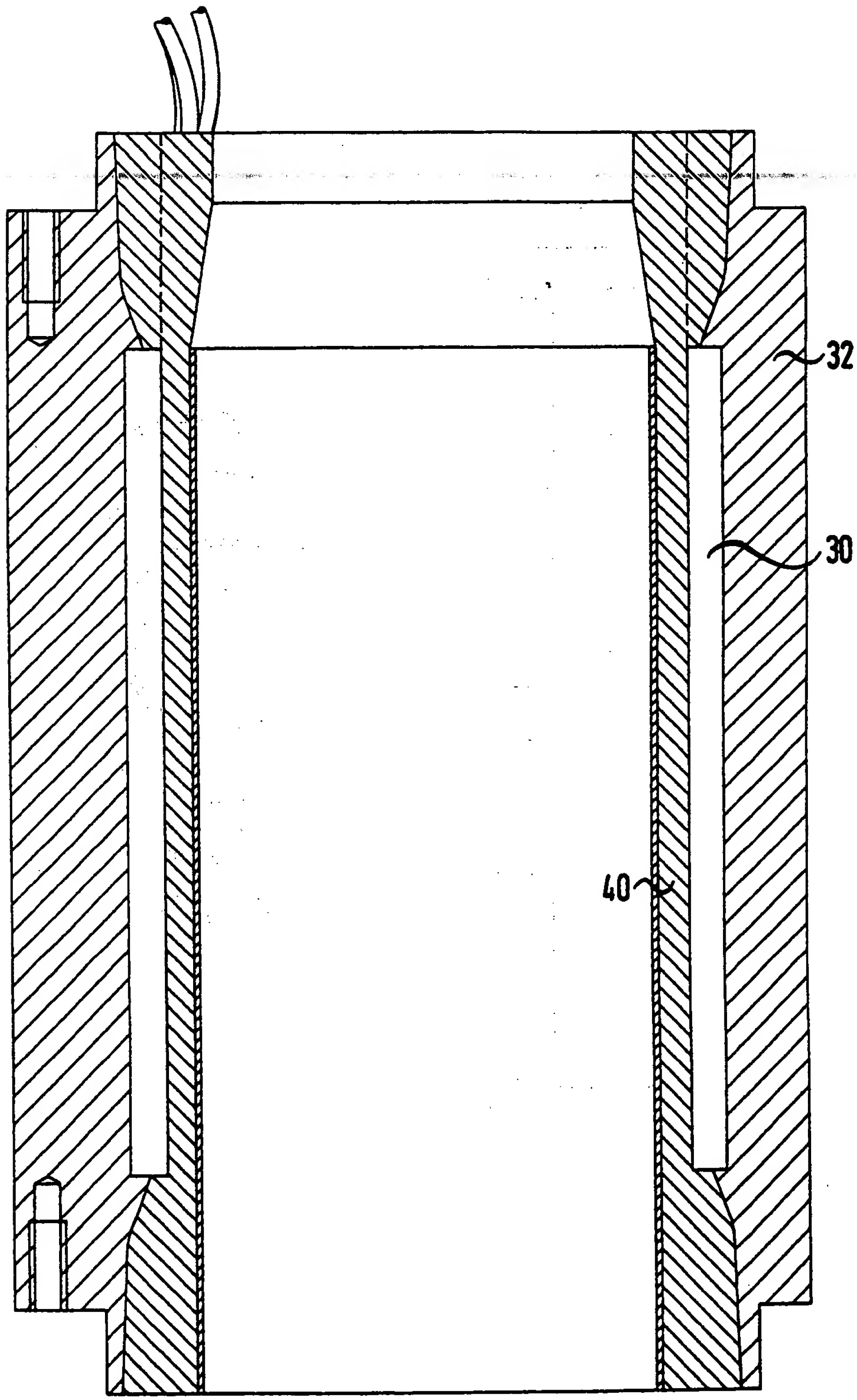


FIG. 3

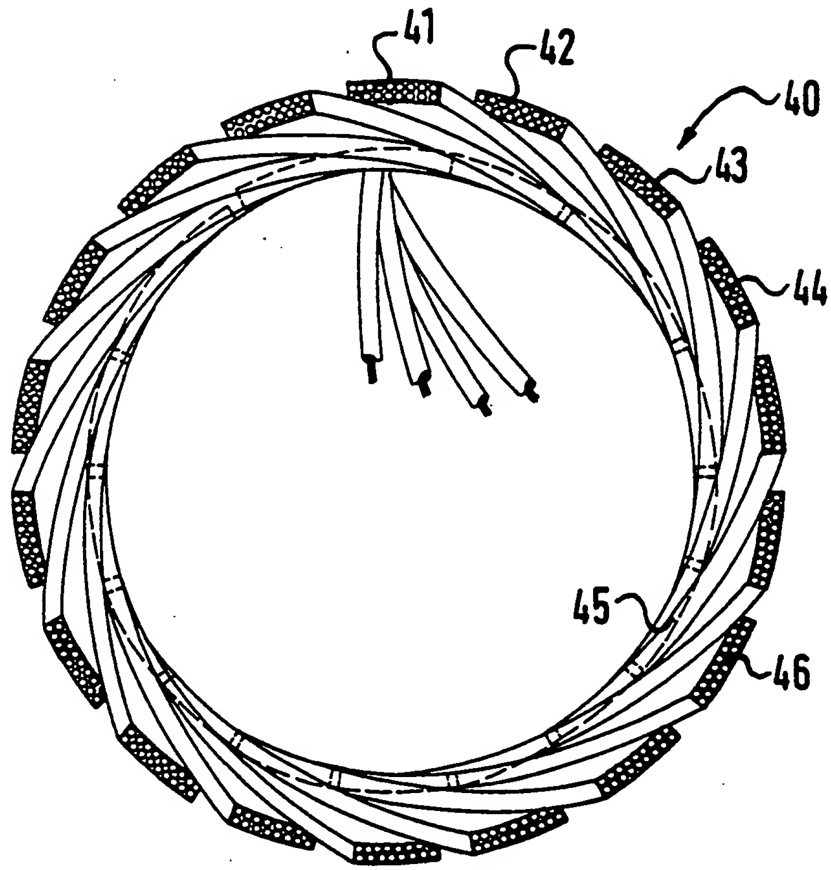
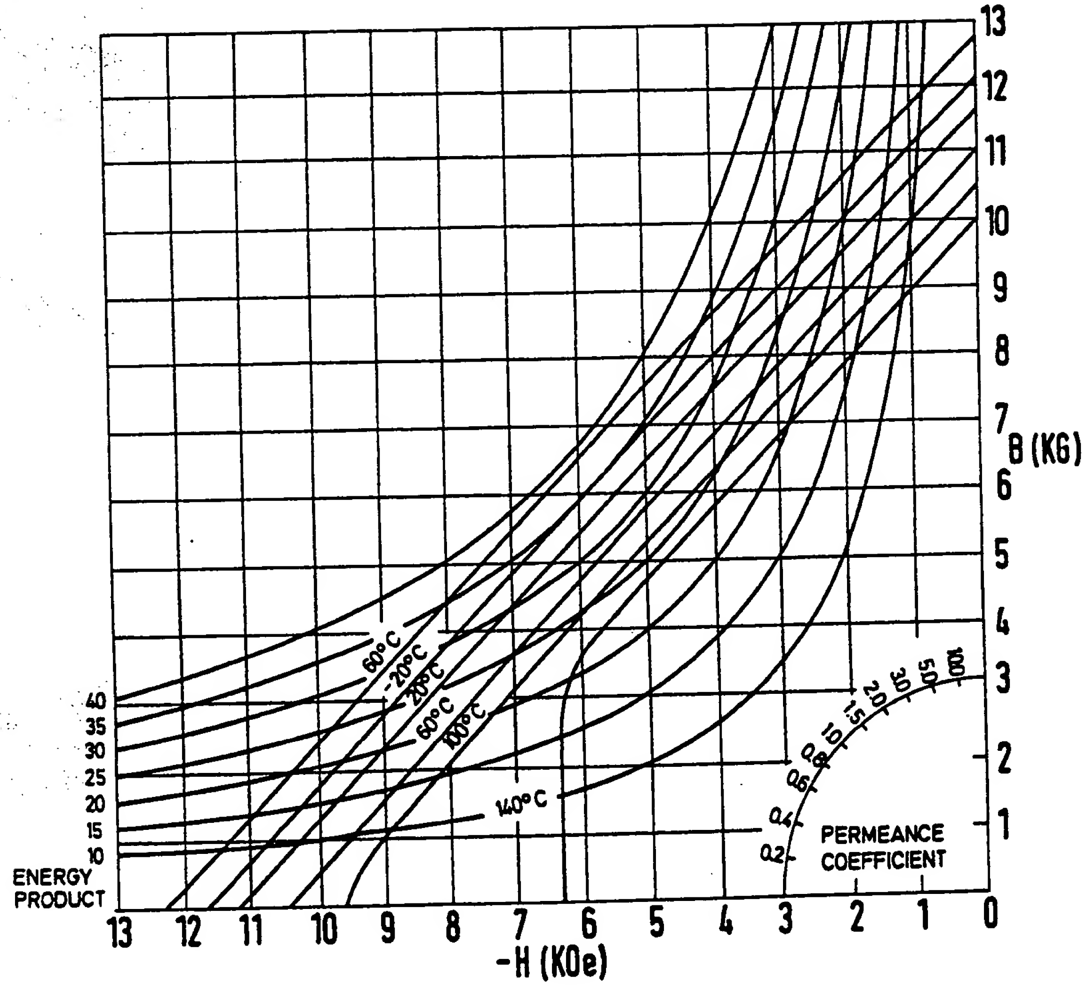


FIG. 4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12
11
10
9
8
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2
1
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-20°C
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60°C
100°C
140°C
40
35
30
25
20
15
10
ENERGY
PRODUCT
100
5.0
3.0
2.0
1.5
1.0
0.8
0.6
0.4
0.2
PERMEANCE
COEFFICIENT
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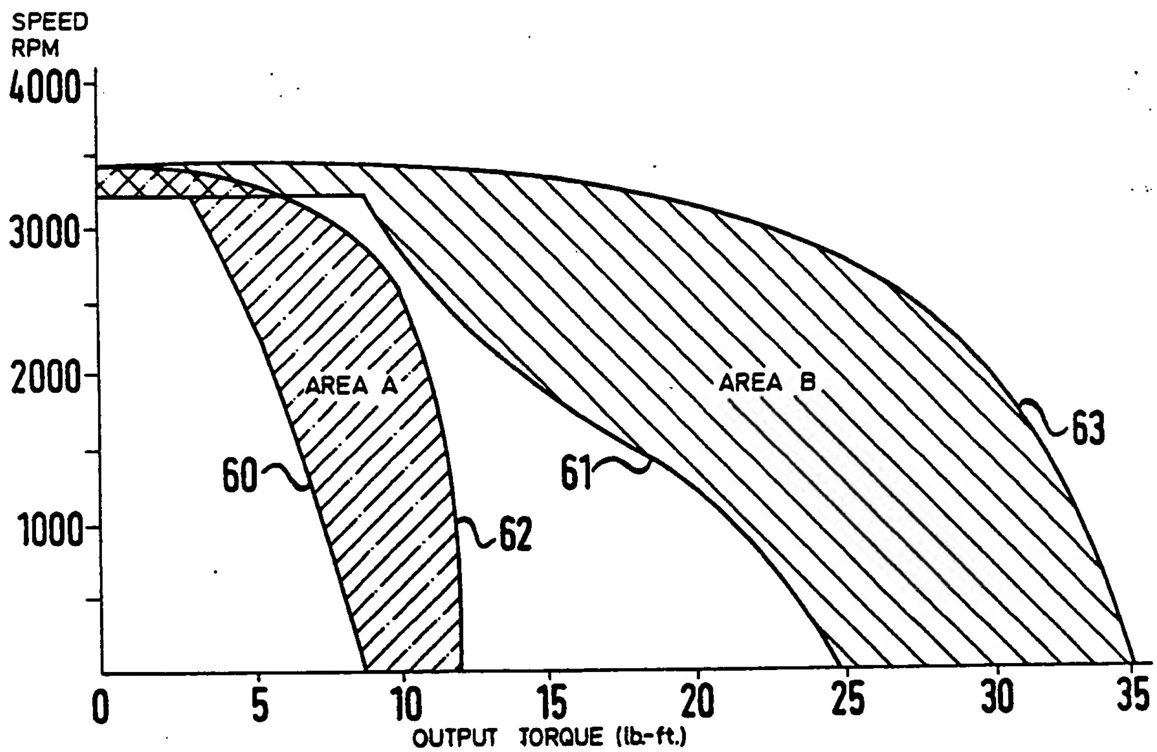
-H (KOe)

FIG. 5


SPEED
RPM
4000
3000
2000
1000
0
5
10
15
20
25
30
35
OUTPUT TORQUE (lb.-ft.)
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AREA B
60
61
62
63

FIG. 6

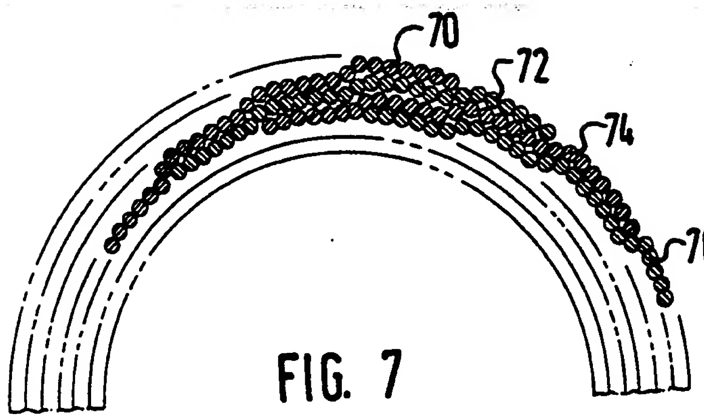

FIG. 7

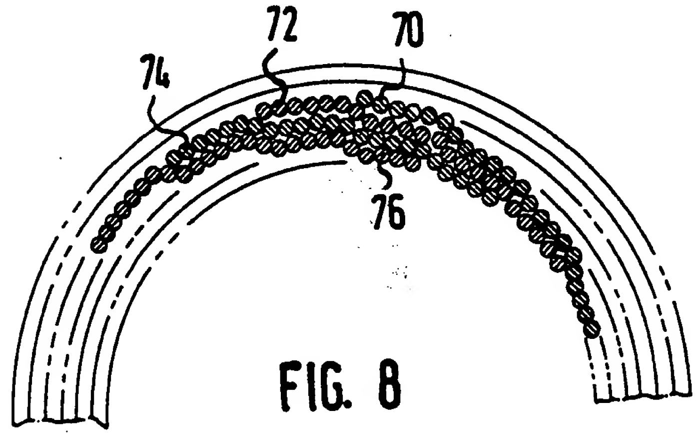

FIG. 8